LECTURE AND DEMONSTRATION ON FLAME PROPAGATION AND PERMISSIBLE AND EXPLOSION-PROOF ELECTRICAL EQUIPMENT

By Hal H. Engel and W. M. Merritts

* * * * * * * * * * * * information circular 7980

UNITED STATES DEPARTMENT OF THE INTERIOR
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BUREAU OF MINES
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LECTURE AND DEMONSTRATION ON FLAME PROPAGATION AND PERMISSIBLE AND EXPLOSION-PROOF ELECTRICAL EQUIPMENT[1/4]

by

Hal H. Engel[2] and W. M. Merritts[3]

SUMMARY

This publication was written in response to numerous requests for information about the Federal Bureau of Mines' "Demonstrated Lecture on Flame Propagation and Permissible and Explosion-Proof Electrical Equipment." The requests came principally from: (1) Persons wanting to know more about the demonstration before requesting it for groups they represented; (2) persons wishing advance information to help publicize a meeting where the demonstration was to be given; and (3) members of audiences desiring something to help them remember the salient points, facts, and figures presented during the lecture and demonstration.

The purpose of the demonstration that accompanies the lecture is to show: (1) Variations in flame speed and pressure at various percentages of flammable gas within the flammable range; (2) effect of flame speed on the "pressure piling" within the area confining the mixture; and (3) the application of flame speed and pressure piling to the combustion of surrounding gas and to the design and maintenance of electrical equipment used in hazardous locations.

The part of the demonstration devoted to the use of explosion-proof and permissible equipment proves that correct installation and maintenance of such equipment are necessary to insure that flame will not pass to the outside. The most satisfactory proof of the safety of an electrical enclosure is its ability to withstand the stresses and strains that occur when an explosive mixture filling the enclosure is ignited. Test explosions inside approved electrical equipment should not result in: (1) Discharge of flame from a joint, bearing, or opening; (2) ignition of surrounding explosive mixtures; (3) development of dangerous internal afterburning; or (4) rupture

1/ Work on manuscript completed July 1959.

2/ Safety representative, Health and Safety District B, Bureau of Mines, Pittsburgh, Pa.

3/ Health and safety engineer (Mineral Industries), Health and Safety District B, Bureau of Mines, Pittsburgh, Pa.

4/ Equipment used in the demonstration was developed by G. M. Kintz, supervisor, Health and Safety District G, Dallas, Tex., and H. F. Browne, safety engineer, District G, Dallas, Tex.

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or permanent distortion of the enclosure. An enclosure should be rejected if any of these conditions occur, if abnormal pressures are developed, or if potentially hazardous conditions are exhibited by the explosions.

Demonstrations will show that poorly maintained electrical enclosures designed to maintain tight joints permit the passage of flame and hot particles when explosions travel through 12 feet of 3/4-inch conduit and into the enclosures. Illustrated, will be explosion hazards connected with the use of poorly maintained electrical equipment; enclosures with loose cover bolts; warped, defaced, and insufficient flange joints; faulty cable outlets and improvised accessories; and other defective fastenings and fittings subjected to explosions that travel through conduit.

This demonstration shows that regardless of how expensive explosion-proof and permissible enclosures are or how carefully they are installed, only a false sense of security exits unless the equipment is properly maintained.

INTRODUCTION

The lecture on flame propagation and explosion-proof and permissible equipment is part of the Federal Bureau of Mines program in accident prevention. To have an effective and realistic demonstration to accompany the lecture, Bureau of Mines engineers have developed equipment for reproducing, on a laboratory scale, fires and explosions that are similar to those that have occurred in the mineral and allied industries. Few people have ever seen how flame travels through a mine, sewer, or pipe; how pressures build up as that flame travels; or how the pressures can cause stoppings or pipelines to rupture or sewer manhole covers to be blown off.

Numerous requests for reproductions of the lecture narrative used with the demonstration led to the preparation of this brief account of the successive steps used in presenting the demonstration.

The lecture is varied somewhat in accordance with the time available and the interests of the audience. Even the approach to the subject will vary, depending on whether the audience is a group from industry, a group from the public in general, or a group of students or firemen. Apparatus used in the demonstration is shown in figure 1.

NARRATIVE

Purpose of Demonstrations

This demonstration is one of several safety educational features presented by the Federal Bureau of Mines and developed in connection with its accident-prevention work. The extent of damage done by an explosion of flammable gas in a building, sewer, pipeline, coal mine, or other confined space depends mainly upon the speed with which the flame propagates through the space. To understand the fundamentals of flame propagation one must give careful consideration to the speeds and pressures developed by different

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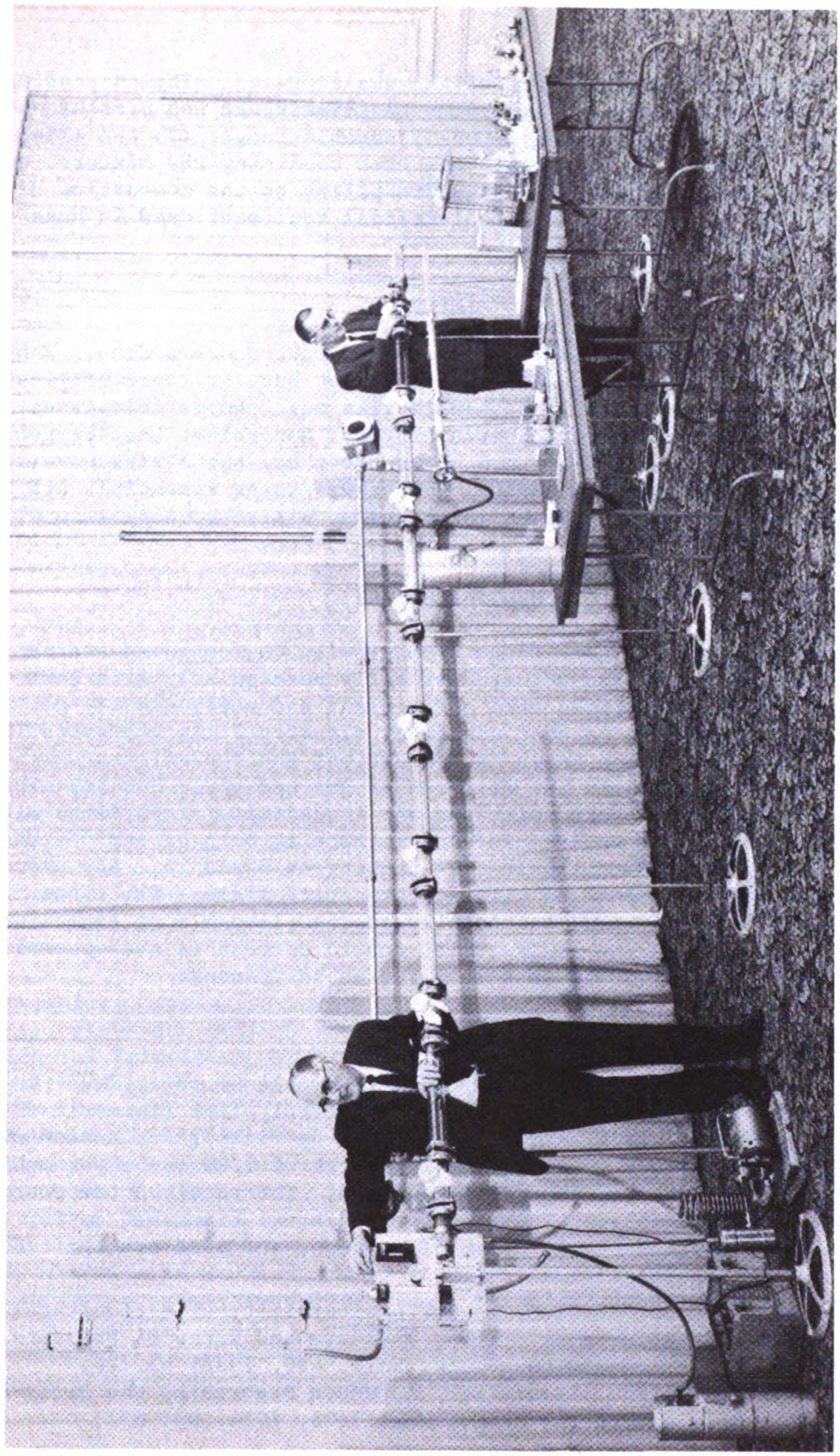

FIGURE 1. - Horizontal Tubes (21-foot) Used in "Propagation of Flame" Demonstration.

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mixtures within the flammable range of the gas or gases. The purpose of the demonstration is to show: (1) Variations in flame speed and pressure at various hydrocarbon gas-air mixtures in the flammable range; (2) the effect of flame speed on pressure piling within the area confining the mixture; and (3) the application of flame speed and pressure piling to the combustion of gas and to the design and maintenance of electrical equipment used in hazardous locations.

Fires

In general, fuel, air, and heat are needed to produce a fire. Many materials (wax, oil, gasoline, and coal) will not burn in their original state but must be vaporized. These vapors like most combustible gases, will not burn until they are mixed with oxygen. Generally, that oxygen comes from the air. Fuel and air can occur together, but a fire usually will not develop until heat is added. When these three essentials are present under precise conditions or formulation, a fire or explosion will result.

Manifestations

The manifestations of fire range from glowing charcoal and ordinary coal or gas fires, which when adjusted properly burn quietly with luminous or nonluminous flames, to fires that are violent and noisy and may get out of control resulting in structural damage or disaster. All are variations of the same chemical process known as combustion; and the effects depend upon many factors, especially the mixtures of gas and air. For any substance to burn in air it must be mixed with the air in definite proportions within the flammable limits. As an example, for methane to burn or explode the percentage by volume of methane in air must be between 5 and 15. Any amount above or below these percentages will not propagate flame. The range from 5 to 15 percent methane is known technically as the flammable or explosive range of methane; 5 percent is the lower limit, and 15 percent is the upper limit. Table 1 gives flammable limits of some selected substances.

Explosion Facts

There are over 130 dusts that may form flammable mixtures.[5] [6] The general requirements for a dust explosion are: A fairly fine flammable dust, finer than granulated sugar (preferably 20-mesh or finer); suspension of the dust in air (a dust cloud) in an amount in excess of 1/20 ounce per cubic foot of air; and, finally, a source of ignition. The required temperature of the ignition source varies considerably for different flammable dusts; virtually all can be ignited by the flame of a match, and some are ignited at unbelievably low temperatures.

5/ Edwards, Paul W., and Leinbach, L. R., Explosibility of Agricultural and Other Dusts as Indicated by Maximum Pressure and Rates of Pressure Rise: U.S. Department of Agriculture Tech. Bull. 490, 1935, pp. 24.

6/ National Fire Protection Association, Advanced Reports to the Fifty-Eighth Annual Meeting, Washington, D. C., May 17-21, 1954, pp. 557.

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TABLE 1. - Flash point, vapor density, ignition temperature, and flammable limits of combustible vapors and gases

	Flash point,[1] °F.	Vapor[1] density (air=1.0)	Selected[2] minimum ignition temperature, °F.	Flammable limits,[3] concentration by volume, percent
Liquids:				
Acetone	0	2.0	1,040	2.6 -13.0
Alcohol (ethyl)	54	1.6	738	3.3 -19.0
Ether (ethyl)	-50 or less	2.6	345	1.8 -36.0
Ethyl mercaptan	80 or less	2.1	570	2.8 -18.0
Gasoline (60 octane)	-50	3.7	536	1.4 - 7.6
Gasoline (100 octane)	-	-	800	1.4 - 7.6
Kerosine	100-165	4.5	444	.7 - 5.0
Naphtha (Stoddard solution)	100-110	3.0-4.0	444	.74- 5.6
Petroleum ether	-69	2.5	550	1.4 - 5.9
Turpentine	95	4.8	491	.8 - ?
Gases:				
Acetylene		.9	581	2.5 -81.0
Ammonia		.6	1,204	15.0 -28.0
Butane		2.0	761	1.9 - 8.5
Blast furnace gas				35.0 -74.0
Carbon monoxide		1.0	1,130	12.5 -74.0
Coal gas			1,200	5.3 -32.0
Coke oven gas				4.4 -34.0
Cyclopropane		1.4	928	2.4 -10.0
Formaldehyde		1.1	806	7.0 -73.0
Hydrogen		.07	1,085	4.0 -75.0
Hydrogen sulphide		1.2	500	4.3 -45.0
Methane		.6	999	5.0 -15.0
Producer gas				14.1 -74.0
Propane		1.5	871	2.1 - 9.5
Sewer gas			1,170	7.5 -19.0

1/ Patty, Frank A., editor, Industrial Hygiene and Toxicology. Volume I, General Principles; 2d rev. ed., Interscience Publishers, Inc., 250 Fifth Ave., New York 1, N.Y., 1958, 830 pp.

2/ Lewis, Bernard, Report of Research and Technologic Work on Explosives, Explosions, and Flames, Fiscal Years 1947 and 1948: Bureau of Mines Report of Investigations 4502, 1949, 92 pp.

3/ Coward, H. F., and Jones, G. W., Limits of Flammability of Gases and Vapors: Bureau of Mines Bull. 503, 1952, 155 pp.

A flammable mixture of gases, such as methane and air, may be diluted with one of its constituents or with other gases until it is no longer flammable. A dilution limit of flammability, or simply a limit of flammability is a borderline composition; a slight change in one direction produces a flammable mixture and in the other direction, a nonflammable mixture.

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Different Types

The Bureau of Mines has an experimental mine in Bruceton, Pa., where thousands of people have witnessed the tremendous force with which the flames of gas, coal dust, and a combination of the two emerged from the mine portal. Some men have been inside the mine when an explosion occurred and have seen the explosion travel away from them. But no one has seen how the flame acted between the ignition point and the portal of the mine.

In this laboratory demonstration one is able to see how pressure develops ahead of a flame and how flame travels through a mine, a sewer, an electrical conduit, or a small container.

Gas

To investigate or determine the cause of a gas explosion it is often necessary to understand the changes in flame speed and pressures when a mixture burns within a confined space.

When flammable gas mixture is placed in tubing closed at one end and the mixture is ignited at the closed end by a source of heat, the flame of the burning gas will travel with rapidly increasing velocity toward the open end. The process of igniting the gas is as follows: If the heat supplied by the ignition source is at the lowest ignition temperature of the gas, the gas in immediate contact with this ignition source may be burned, but the amount of heat generated is insufficient to cause ignition of the unburned gas that envelops the burning layer. However, if the source of ignition has enough heat to raise the thin layer of gas surrounding the flame above its ignition point, then the heat from the combustion will be sufficient to ignite the adjoining layer of gas. The resulting combustion flame will pass through the next layer with increasing velocity, as follows:7/

> After a flammable mixture has ignited, the flame travels initially at a speed which depends upon a number of conditions, such as mixture composition, turbulence, temperature, pressure, time from ignition, obstructions, releases, etc. Within certain mixture compositions and under certain other not-too-well understood conditions, ordinary flames may undergo transition to detonation, which is a flame traveling at speeds well above the velocity of sound.
>
> One of the fastest gas detonations known occurs in a mixture of about 89 percent hydrogen and 11 percent oxygen. When ignited at atmospheric pressure, this mixture has a flame speed of over 2 miles per second.

7/ Scott, G. S., Kennedy, R. E., and Zabetakis, M. G., Gas Explosions and Their Prevention: Bureau of Mines Inf. Circ. 7601, 1951, 13 pp.

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Vapor[8]

The vapors of combustible liquids have limits of flammability just as do true gases. However, in the case of vapors, the limits may be expressed in terms of temperature as well as concentration.

Dust

Gas and dust explosions are quite similar. Gas explosions require a mixture of the gas with air in definite proportions; dust explosions require intimate mixture of the dust and air in definite proportions, and the dust must be in a cloud. Both explosions require a certain amount of heat from the ignition source to start initial combustion; any smaller amount of heat will fail to ignite the gas or dust, and an explosion will not occur. After initial ignition, the heat generated by combustion of the dust must ignite the adjoining dust, and the flame will travel through the dust cloud with increasing velocity.

Some Major Explosions

Manchuria (1942): Coal-mine dust explosion; rated worst dust explosion in history; 1,527 dead.[9]

Cleveland, Ohio (1944): Flammable-liquid tank explosion; 128 dead.[10]

Texas City, Tex. (1947): Ammonium nitrate ship explosion. (This material is used by farmers as a fertilizer); 568 dead (estimated); many bodies never found.[11]

8/ Work cited in footnote 7.

9/ The Honkeiko Colliery Disaster: Colliery Eng., vol. 24, No. 283, September 1947, pp. 281-316.
Warncke, Russel G., Observations of Safety Practices and Conditions in Japanese Coal Mines: Bureau of Mines Inf. Circ. 7542, 1949, pp. 38.

10/ Elliott, M. A., Seibel, C. W., Brown, F. W., Artz, R. T., and Berger, L. B., Report on the Investigation of the Fire at the Liquefaction, Storage, and Regasification Plant of the East Ohio Gas Co., Cleveland, Ohio, Oct. 20, 1944: Bureau of Mines Rept. of Investigations 3867, 1945, pp. 44.

11/ Fire Prevention and Engineering Bureau of Texas, Dallas, Tex., and National Board of Fire Underwriters, New York, N.Y., Texas City, Tex. Disaster. April 16, 17, 1947, p. 4.
Armistead, George, Jr., The Ship Explosions at Texas City, Texas, on April 16 and 17, 1947, and Their Results: Washington, D.C.
National Fire Protection Association, The Texas City Disaster: Quarterly, vol. 41, No. 1, July 1947, pp. 25-27.
Kintz, G. M., Jones, G. W., and Carpenter, C. B., Explosions of Ammonium Nitrate Fertilizer on Board the S. S. Grandcamp and S.S. High Flyer at Texas City, Texas, Bureau of Mines Rept. of Investigation 4245, Feb. 1948, pp. 57.

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Chicago, Ill. (1921): Grain dust explosion; 40 storage bins weighing about 300,000 tons were lifted off their bases; 6 dead.[12/]

The Bureau of Mines is always alert to discover conditions that may lead to coal-dust and methane-gas explosions in the Nation's coal mines, as well as gas and flammable fuel-vapor explosions in the petroleum and allied industries. Techniques for preventing such explosions have been developed through careful study and experimentation. Details of these techniques will be discussed while demonstrating applicable items.

DEMONSTRATIONS

The demonstrations described usually follow the preliminary remarks. Of course, additional pertinent comments are made during the demonstration. A narrative of the points at issue accompanies each item of the demonstration. Explosive limits of the gases used are discussed, and known local gas-explosion tragedies are mentioned at fitting times.

List of Equipment Used in Demonstrations

1. 4 feet of 2-inch Pyrex glass tubing.
2. 4 feet of 1-inch Pyrex glass tubing.
3. 21 feet of 2-inch Pyrex glass tubing with 8 evenly spaced 2-inch-diameter lateral openings covered with paper diaphragms.
4. 12 feet of 3/4-inch conduit and miscellaneous electrical equipment.
5. Gas burner.
6. Bottle of propane gas.
7. Air compressor.
8. Electric motor.
9. Gas-air mixing control panel.
10. Electrically operated foot switch.
11. 10 units of explosion-proof and permissible electrical equipment.

12/ Price, David J., and Brown, Harold H., Dust Explosions, Theory and Nature of, Phenomena, Causes, and Methods of Prevention: National Fire Protection Association, Boston, Mass. (about 1922), pp. 246.

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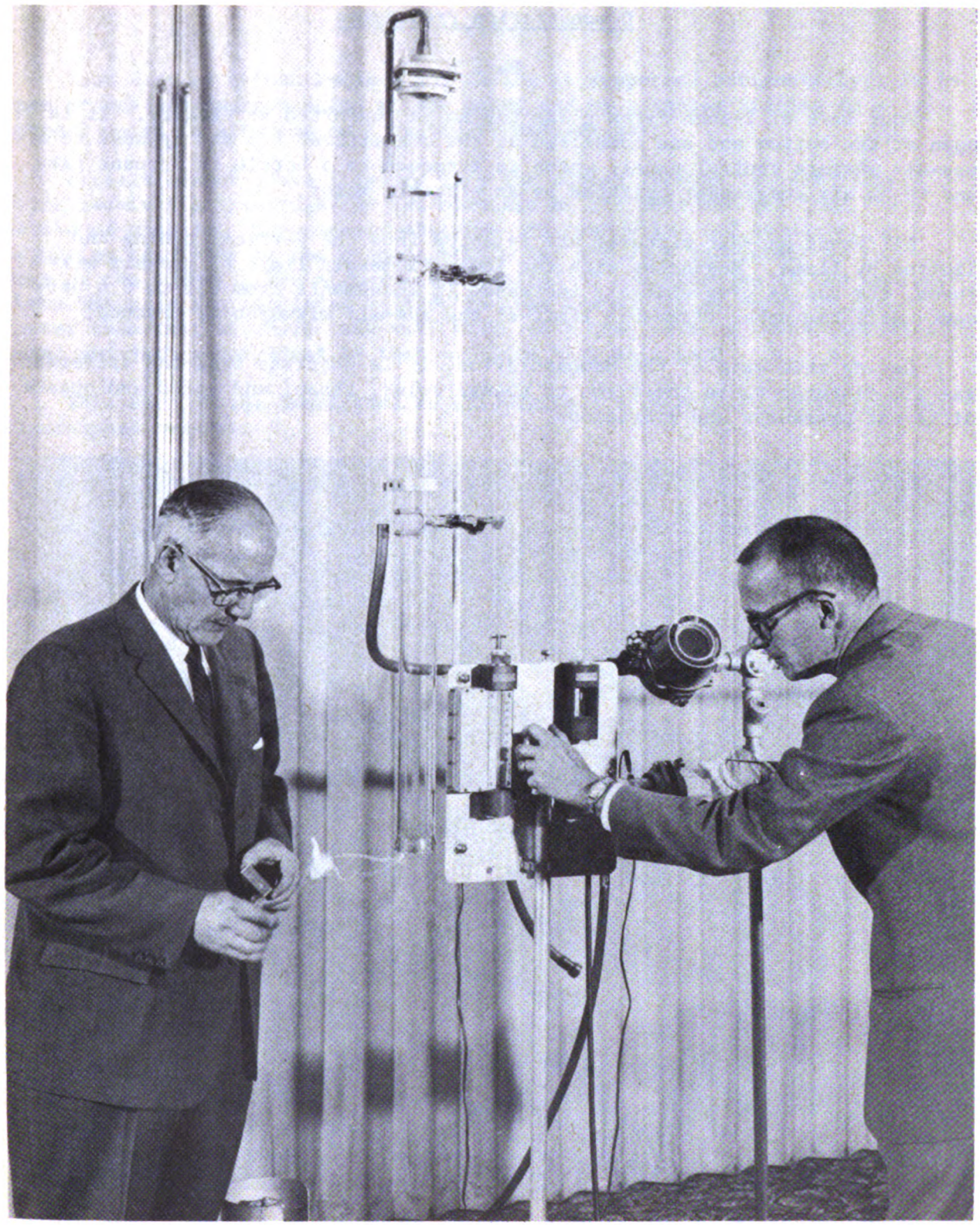

FIGURE 2. - Igniting Rich Mixture in Vertical Tube Used in "Propagation of Flame" Demonstration.

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Demonstration Procedures

Part A

Four feet of 2-inch Pyrex glass tubing is supported vertically. It is open at the bottom end and connected at the constricted top end by hose to a gas-air mixture control panel, which is attached to a bottle of propane gas and to an air compressor operated by an electric motor.

Different gas-air mixtures are injected into the vertical tubing and ignited by flame. Beginning with the lower flammable limit of gas-air mixtures, the gas is progressively increased in increments from 0.2 to 0.4 percent until the upper flammable limit of the gas-air mixtures is reached.

During this part of the demonstration, it is observed that the different gas-air mixtures cause the flame to change color, shape, and speed and create different pressures and vibrations.

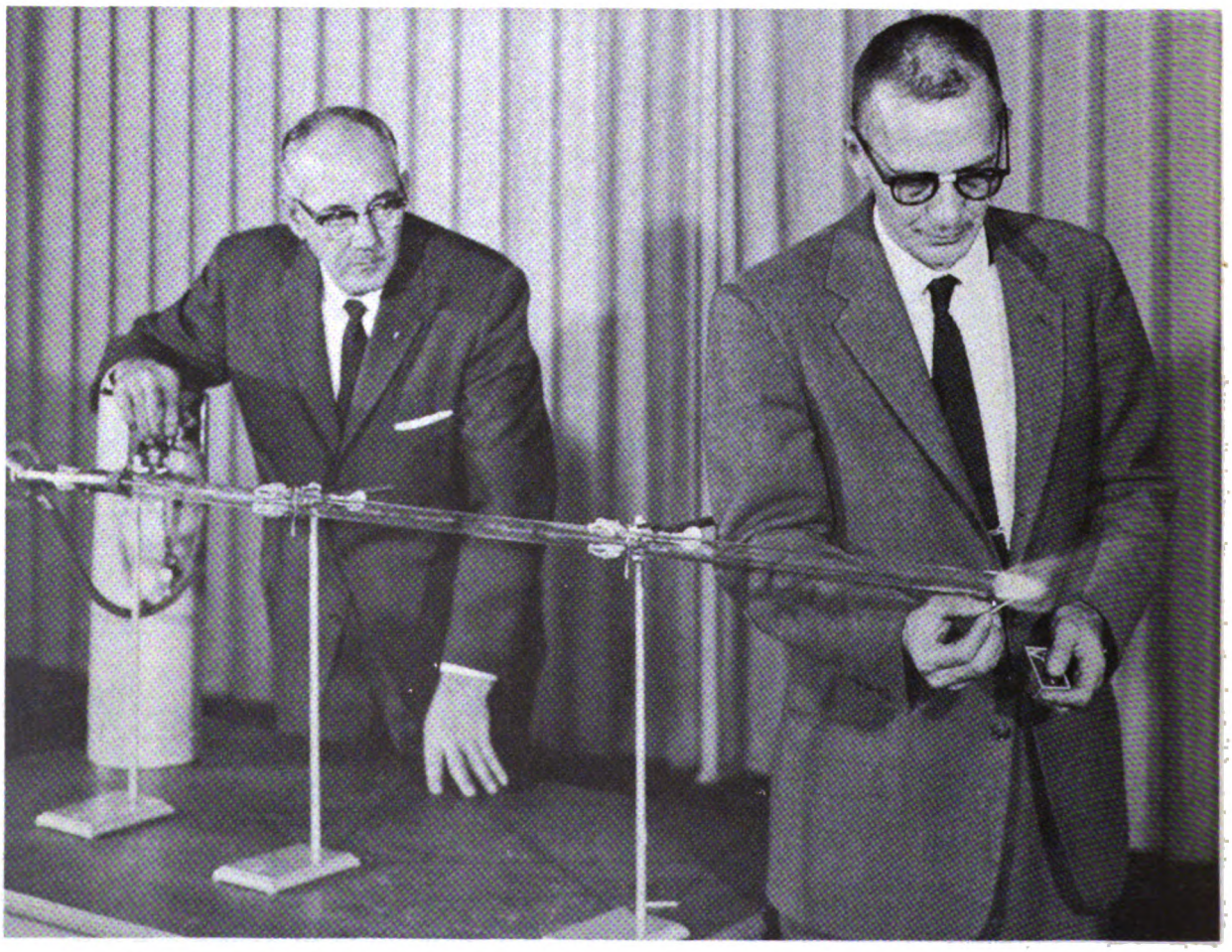

FIGURE 3. - Demonstration of Flame Speeds in Small Horizontal Tube Used in "Propagation of Flame" Demonstration.

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Part B

Four feet of 1-inch Pyrex glass tubing is supported horizontally. It is open at one end and connected at the other end by a rubber fitting to a gas burner, which is attached to a bottle of propane gas.

Gas-air mixtures are injected into the tubing through the gas burner, which receives air through the ven openings at its base and gas from the bottle of propane. The gas-air mixtures are controlled and regulated by adjusting the valve of the propane bottle and the vent regulators at the base of the burner. The mixtures are ignited at the open end of the tubing. These mixtures are regulated to flow through the tubing at rates of speed faster than that at which they will burn, less than that at which they will burn, and just about equal to that at which they will burn.

This part of the demonstration illustrates the practical application of flame-speed control.

Part C

A horizontally supported Pyrex glass tube 2 inches in diameter and 21 feet in length, with eight evenly spaced 2-inch-diameter lateral openings covered with paper diaphragms, is used for this part of the demonstration. The tube is open at one end and connected at the opposite end to a gas-air mixture control panel, which is attached to a bottle of propane gas and to an air compressor operated by an electric motor.

Different gas-air mixtures are injected into the tubing and ignited by flame, either at the open end or at intermediate spaces along the tube, or by an electric arc in the closed end.

In this part of the demonstration the following observations of flame are noted:

1. A mixture near the lower flammable limit is ignited at the open end, and the flame travels back through the tubing slowly and silently but does not set fire to the paper diaphragms. As the flame moves along the tubing, the top edge travels ahead of the lower part of the flame.

2. A similar mixture is ignited by an electric arc at the closed end. The flame travels a short distance, hesitating and moving on, alternatively, until it propagates through the length of the tubing.

3. A rich mixture is ignited at the open end, and the flame "floats" back through the tubing without setting fire to the paper diaphragms.

4. A similar mixture is ignited from the closed end. The explosion behaves like the lean mixture that was ignited from the closed end.

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5. Mixtures corresponding to the entire flammable range are reproduced in the tubing when a flowing mixture above the flammable limit is ignited at the open end where the flame remains. When the percentage of gas in the gas-air mixture flowing through the tubing is decreased slowly into and through the flammable range, the flame starts back into the tubing slowly and travels faster and faster until it reaches the approximate middle of the tubing. There, the percentage of gas in the mixture is equal to the percentage of the gas-air mixture indicated at the top of the flammability curve. Then the flame proceeds more and more slowly until it reaches the lower flammable limit at the closed end of the tubing, where the flame is extinguished.

6. To illustrate how forces develop during an explosion, a Ping-pong ball is placed in the tubing at the fourth lateral opening. The opening is then covered with a paper diaphragm. An explosive mixture is injected into the tubing and ignited from the closed end. As the flame approaches the ball, the latter is pushed ahead for a short distance. The flame overtakes and passes the ball. The ball then returns to the closed end of the tubing.

7. The paper diaphragm is removed from the fifth lateral outlet, and an explosive mixture close to the upper flammable limit is injected into the tubing. As the mixture is discharged through the lateral opening it is ignited by flame. The flame stays on the outside of the opening as long as the mixture is injected through the tubing, even though one end of the tubing is open. When the flow of the mixture is stopped, a "lazy" flame burns above the lateral opening. As the mixture burns, it pulls air into the tubing from the open end. However, the gas in the burning mixture is being reduced. When it is lean enough to form a proper gas-air mixture at the flame, the flame travels into the outlet and out of the tubing at the open end; this effect could cause an explosion.

8. The tubing is then filled with an explosive mixture, which is near the top of the flammability curve, that is, close to the most violent explosive mixture. When the mixture is ignited at the closed end of the tubing, the flame travels with considerable speed, creating pressure and noise. Some of the diaphragms, but not all, appear to have been broken by being sucked into the tubing; none of the diaphragms have been set on fire.

9. A rapid-moving and turbulent mixture of gas and air is ignited in the tubing at the closed end. The explosion travels much faster and with more violence than the other demonstrated gas-air explosions.

Part D

The equipment used in part C of the demonstration is used for gas-dust-air explosions. Explosions resulting from many combinations of coal-dust and gas-air mixtures can be demonstrated in the tubing.

A small quantity of coal dust is placed on a tray which is put in the tubing. The tubing is then filled with an explosive gas-air mixture and the mixture ignited at the closed end. The force of the gas-air explosion raises

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the coal dust in the tray into a cloud that the rapidly advancing gas-air-explosion flame ignites.

Numerous factors concerning dust explosions will be dealt with in detail during this part of the demonstration.

Part E

To illustrate what takes place when explosions occur in permissible or explosion-proof equipment, a 3/4-inch-diameter by 12-foot-long conduit is supported horizontally and connected at each end to approved enclosures equipped with glass covers. This apparatus enables one to see the flame of an explosion as it propagates from one end to the other in the conduit. The approved enclosure on one end of the conduit is connected by hose to the gas-air mixture control panel that was used in part D demonstrations. At the opposite end of the conduit, approved electrical equipment of various types, some in good condition and some in defective condition, is attached to the conduit. In demonstrating the relative safety of the various types of electrical equipment, gas-air mixtures near those producing the most violent explosions are injected into both the conduit and the electrical equipment, then the mixtures are ignited by arcs. Thus, much of the equipment is surrounded by explosive mixtures when the inside mixtures are ignited.

PERMISSIBLE AND EXPLOSION-PROOF EQUIPMENT

Permissible or explosion-proof equipment is approved electrical equipment within which explosions of gas can occur without breaking the case and from which flame or heated particles cannot escape that will be hot enough to ignite the flammable mixture outside the equipment.

Two organizations approve electrical equipment for use in hazardous locations. The Bureau of Mines approves equipment for use in coal mines where atmosphere containing methane and coal dust may be encountered, but it does not approve electrical equipment for other flammable gases. Electrical equipment approved by the Bureau of Mines bears an approval plate, and the equipment is classified permissible. The Underwriters' Laboratories approves electrical equipment for use above ground in areas endangered by, or subjected to, gas and dust-explosion hazards. This equipment is classified explosion-proof.

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